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PERFORMANCE OF M-ARY ORTHOGONAL CONTINUOUS PHASE FSK FOR A TRANS-IONOSPHERIC TIME-VARYING FREQUENCY-SELECTIVE CHANNEL

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Technical Report

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

M-ary Orthogonal continuous Phase FSK modulation can significantly improve severe frequency-selective channel Bit Error Rate over conventional modulation techniques. This modulation technique has the potential to enhance the performance of channel equalizers and error correction and coders in a selective channel.

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18. SUBJECT TERMS (Continued).

   Channel Equalization
   Frequency-Shift-Keying

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SECTION 1

M-ARY FSK BACKGROUND

1.1 INTRODUCTION

This report summarizes the results of a study to compare
the performance of channel equalized high data rate PSK with
that of M-ary FSK to mitigate *frequency selective fading*.

1.2 M-ARY FSK BACKGROUND

In the past, as far as modulation is concerned, to
mitigate selective fading one usually went to a narrow
bandwidth signal so that the distortion was minimized. This
is the basic idea behind going to M-ary FSK. Proakis [3]
defines a spread factor $T_m * B_d$ which is proportional to
$1/(f_o * t_o)$ where f_o is the frequency coherent bandwidth and
t_o is the decorrelation time of the channel. He states that
if the spreading factor is less than 1, the channel is
underspread and if it is greater than 1, the channel is
overspread. If the channel is underspread, then it is
possible to to break the signal into several lower data rate
signals and then frequency multiplex them together such that
the channel is frequency nonselective and slowly fading for
each *narrow band subsignal*. Thus, for an uncoded non-
diversity system flat fading performance can theoretically be
achieved in an underspread selective channel. This aproach
can essentially be implemented by going to M-ary FSK
modulation and selecting the modulation index appropriately.

SECTION 2

M-ARY ORTHOGONAL CPFSK

This approach is to employ the advantages of M-ary Orthogonal Continuous Phase FSK, (M-ary O-CPFSK). The modulation technique was choosen for several reasons. First of all, since the channel is dispersive, (i.e., it has a large delay spread relative to the bit period), Inter-Symbol Interference (ISI) is a significant problem. To reduce the ISI, one can go to higher signaling sets to increase the symbol length with respect to the delay spread. As an example, if we define R_d as the data rate, and let R_d/f_o be 3 bits, a 64-ary symbol set would have less ISI/symbol than that of a 32-ary symbol set. (Assuming the same overall information rate). This will be shown via the probability of error curves in section 4. Note though, that one approaches the law of diminishing returns rather quickly. In going from a 64-ary system to a 128-ary, (a rather significant task), one gains only an additional bit period in symbol length. For the purposes of this report, 64-ary was the largest symbol set simulated.

Orthogonal CPFSK has a modulation index of 1 (instead of 1/2 for Minimum Shift Keying (MSK) or Fast Frequency Shift Keying (FFSK), for example). The modulation index is the separation of the frequency tones normalized to the symbol rate. An index of performance is the spectral efficiency which is a ratio of the data rate to the modulation bandwidth. For example binary CPFSK with a modulation index of 1/2 (FFSK)

has a theoretical spectral efficiency of 2 bits/sec/Hz, whereas, binary O-CPFSK is only 1 b/s/Hz. Hence, O-CPFSK is not particularly spectrally efficient. This inefficiency is compensated for somewhat by the fact that we are using an M-ary system. This is because larger signaling alphabets provide longer symbol periods, hence smaller symbol rates and thus closer tone spacing.

The use of M-ary O-CPFSK has not been widespread because of its spectral inefficiencies and the extra power required for a specified bit error rate. The spectrum, however, does have the important quality that it is composed of M - discrete spectral lines and low sidelobes, (See reference [1]). Figure 2-1 shows the spectrum of 4-ary O-CPFSK. A significant portion of the energy of the signal resides at these single frequencies. This signaling scheme can be viewed as a set of M frequency multiplexed On-Off Keyed (OOK) narrow band RF carriers. Thus, when it is passed through a selective channel, (see figure 3-2), the ISI is minimized because the phase is approximately linear over a narrow band. Hence, if a channel has a linear phase characteristic, the ISI is zero. Of course, the ISI is not completely eliminated in the O-CPFSK case because there is some energy between the spectral lines (see figure 2-1) that must be used to reconstruct the signal at the receiver. However, the important point to note is that a good portion of the energy of the signal resides at these discrete lines and hence, to a good approximation, the channel looks now like a flat-faded channel, (with a different fade level for each tone). This is essentially what Proakis [3] had suggested for an underspread channel.

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In contrast, suppose that one were to use ordinary BPSK modulation. The spectral characteristics of this modulation is a $(\text{Sin}(x)/x)^2$ shape with a first null at $1/(2*T_b)$. The spectrum is more uniformly distributed over the channel passband than the equivalent RF bandwidth 4-ary 0-CPFSK. However, when BPSK is passed through a selective channel, the phase distortion, (ISI), will be more severe than that of the 0-CPFSK as will be shown in Section 4.
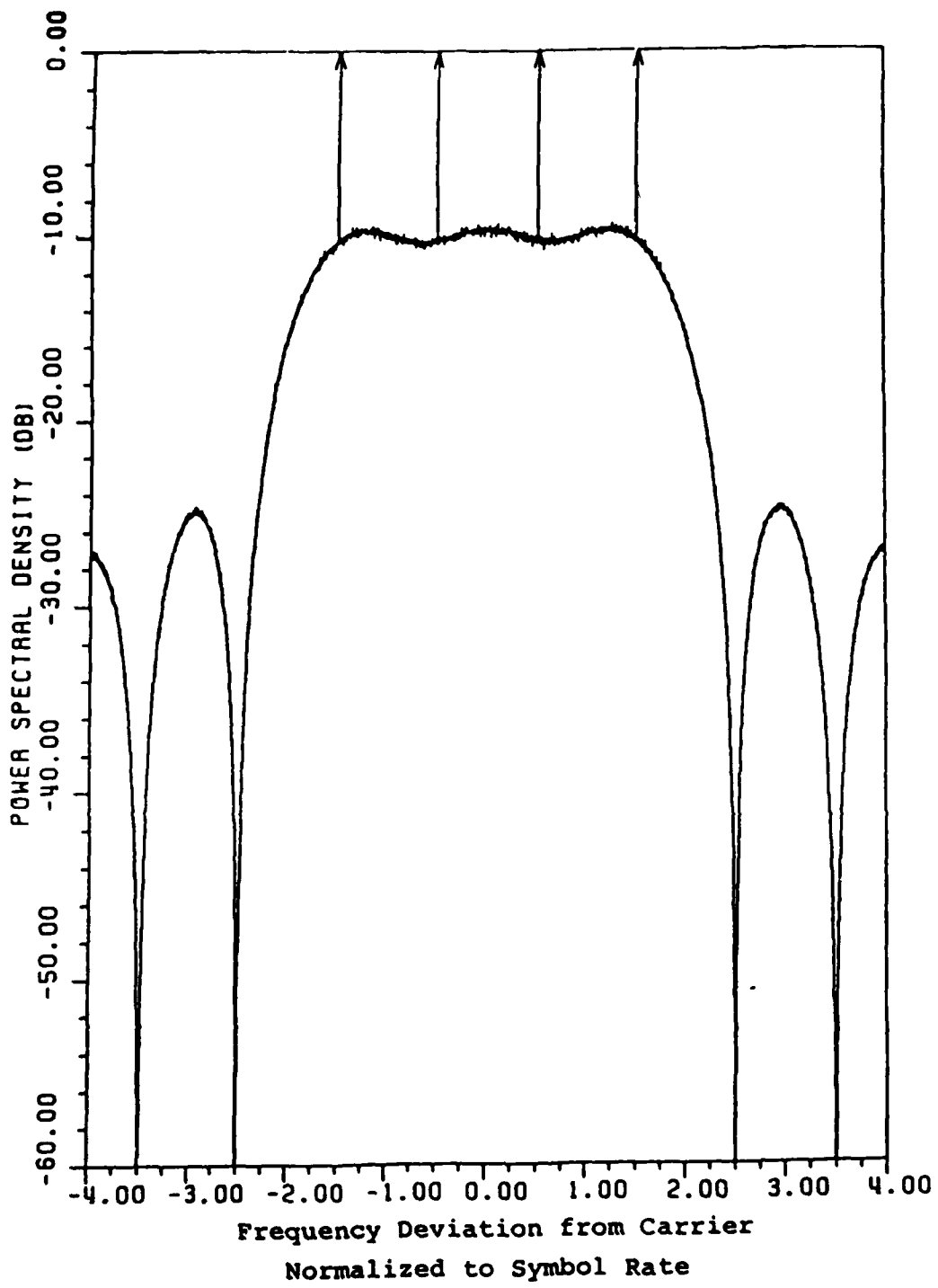
Figure 2-1   Power spectrum of 4-ary O-CPFSK modulation

SECTION 3

SIMULATION AND ASSUMPTIONS

The modulator-channel-demodulator simulation was performed on a VAX 11/750 computer. The channel was modeled using CIRF, (Channel Impulse Response Function) which is a FORTRAN program that simulates the trans-ionoshperic time-varying frequency-selective channel. The software generates a 2-dimensional (N_d delays by N_t times) array of complex valued samples corresponding to the channel impulse response (in the delay domain) for a block of time. Figures 3-1 and 3-2 show a typical impulse response, channel passband, and envelope delay, respectively, generated by CIRF. (For more information on CIRF see reference [2]). The simulations were performed in the frequency domain using envelope detection for the CPFSK modulation. A correlative noncoherent receiver is assumed and bit-sync tracking is simulated with a single pole recursive filter (update frequency = $R_d/100$). The bit-sync was implemented by maximizing the power out of the matched filters. The DPSK simulation was performed in the time domain assuming perfect bit sync. The channel decorrelation time is $t_o = 1000/R_d$ for all the simulations while the frequency coherent bandwidth (f_o) is varied from $R_d/5$ to $R_d/16$. These results are compared in the next section to DEPSK modulation with Adaptive Maximum Likelihood Sequence Estimation (AMLSE), (see reference [5]).
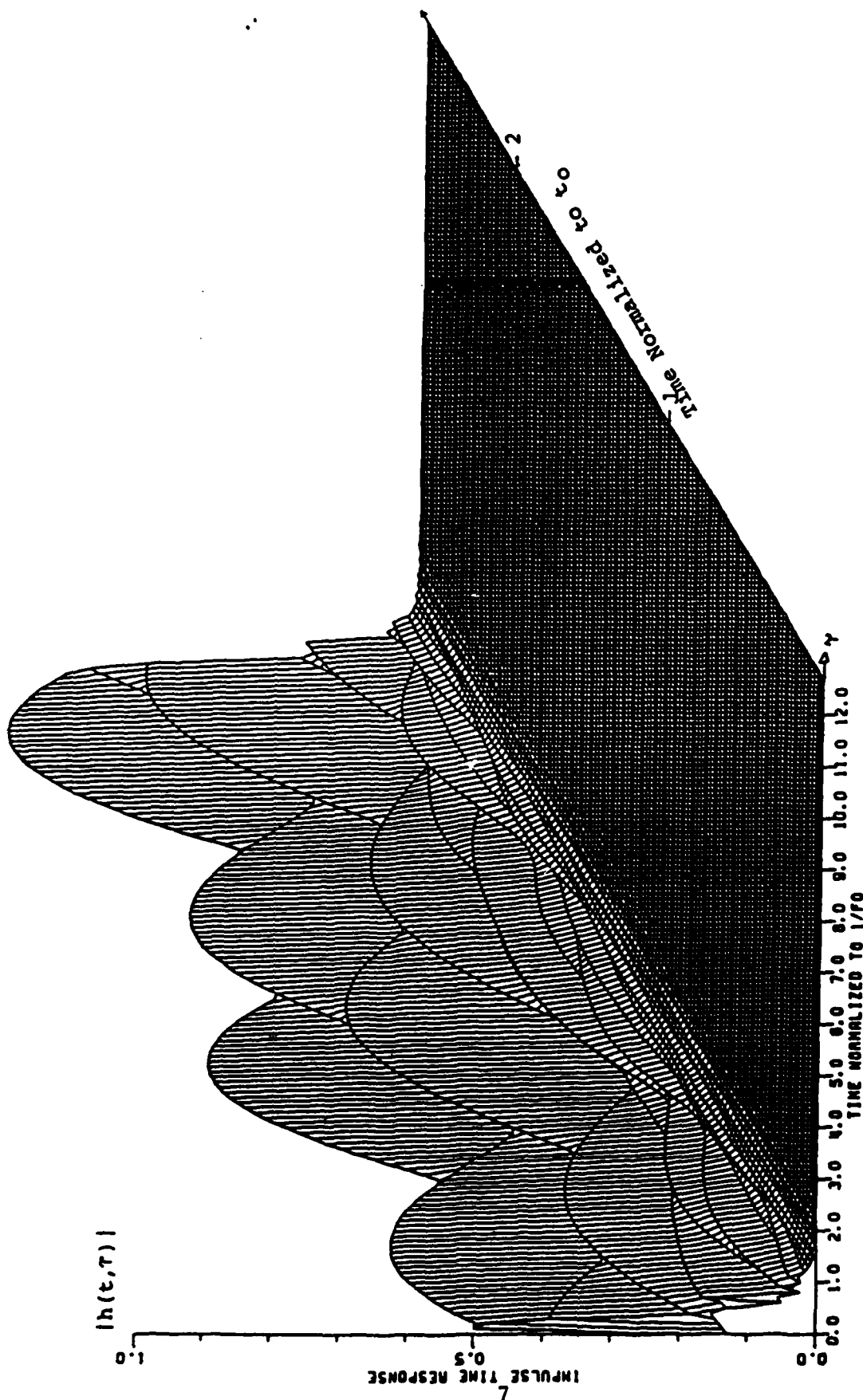
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Figure 3-1 Typical impulse response of a time-varying frequency-selective channel vs. time. This response was generated using CIRF. The horizontal axis is the impulse response delay and the axis into the page is the time variable.
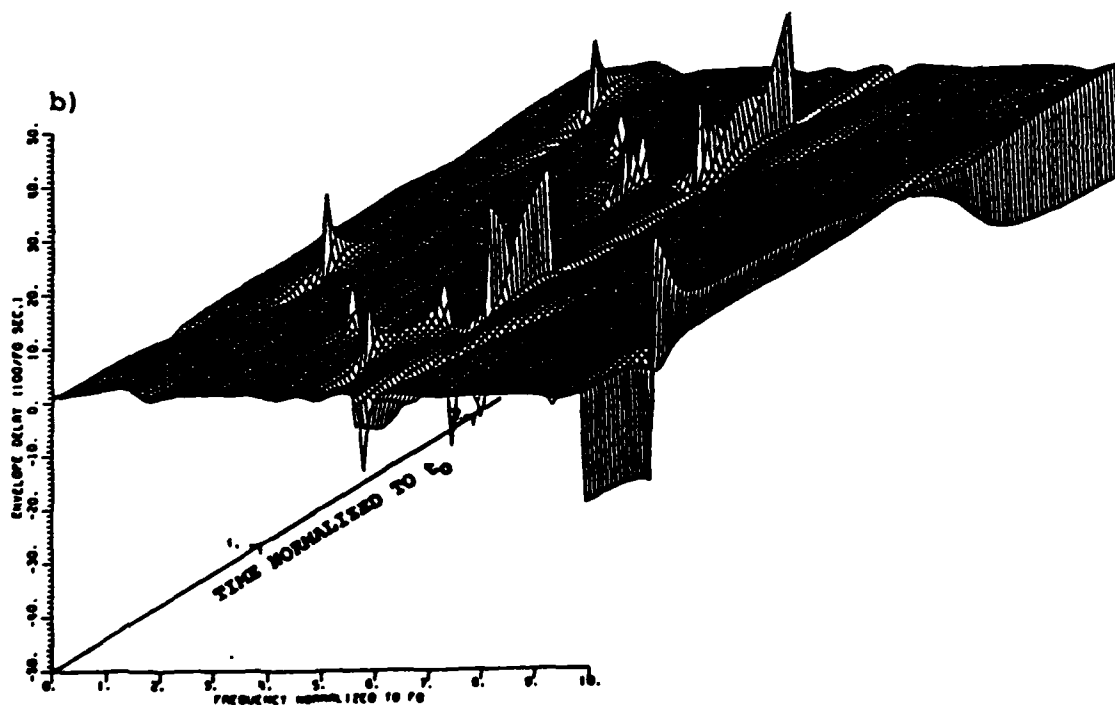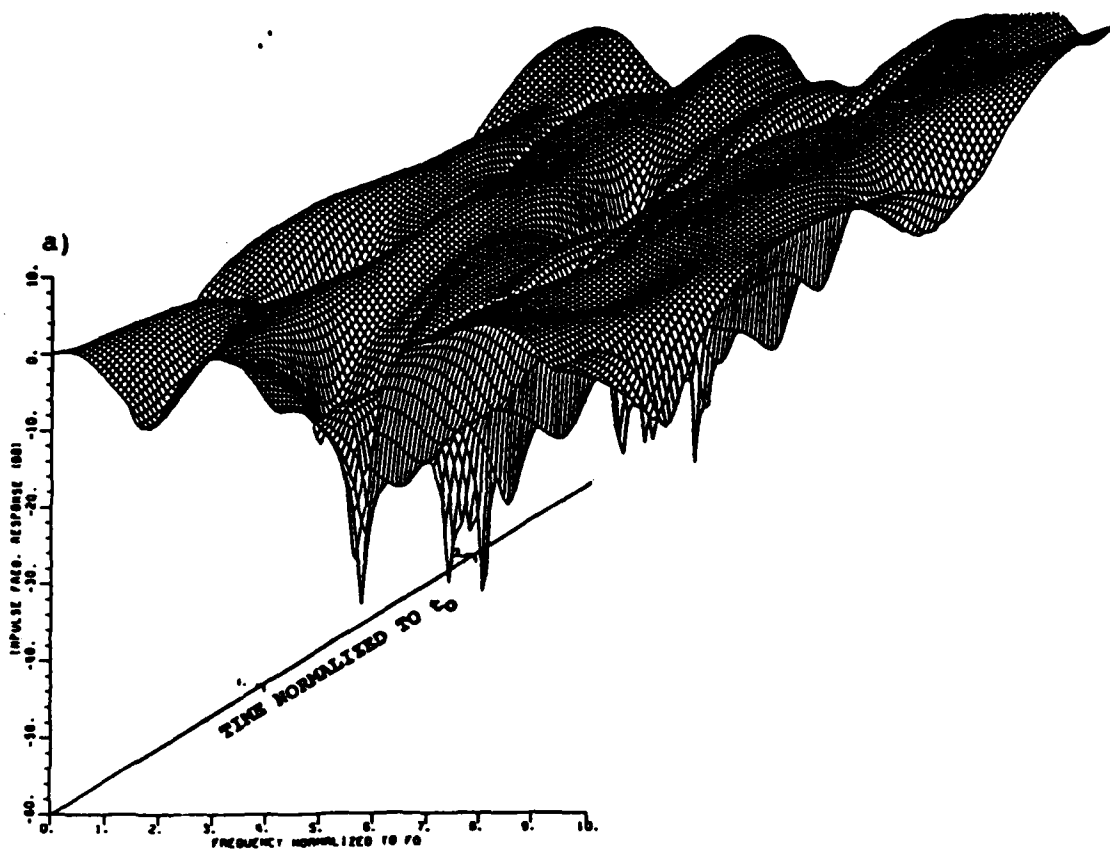
Figure 3-2   Typical passband of a time-varying frequency-
              selective channel as generated by CIRF.
                 a) Magnitude of the channel response vs.
                    time and frequency
                 b) Envelope delay response

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SECTION 4

RESULTS

Figure 4-1 shows a comparison of DPSK and 2-0-CPFSK probability of bit errors (Pe) for a selective channel. Note that the DPSK RF bandwidth is twice the RF bandwidth of the 2-0-CPFSK. The Pe performance of the DPSK is significantly worse than the CPFSK. Also plotted in figure 4-1 is the flat fading cases for both modulations. Notice that DPSK in flat fading actually does better than noncoherent CPFSK in flat fading. This is because DPSK performs better in the benign environment than 0-CPFSK for a given E_b/N_o, and, since flat fading only affects the signal amplitude (without ISI), the same relative performance remains. Figure 4-2 shows a comparison of noncoherent 4-ary orthogonal CPFSK with noncoherent 4-ary orthogonal FSK. The basic difference is that the latter has a random phase transition at the symbol transition whereas CPFSK has no phase jumps between symbols. Note that CPFSK has the superior performance of the two. It is interesting to note that in the ideal channel, both techniques perform the same, while in a selective channel, noncoherent CPFSK is superior to noncoherent FSK. Figure 4-3 shows the performance of larger signalling sets. Note that the 16-ary, 32-ary, and 64-ary 0-CPFSK modulations have not leveled off yet at 25 dB E_b/N_o. Also note that the relative Pe for all except the 2-ary case is beyond the typical equalizer thresholds (of Pe=0.1 to 0.4) and, since ISI is significant, equalization will improve the performance.
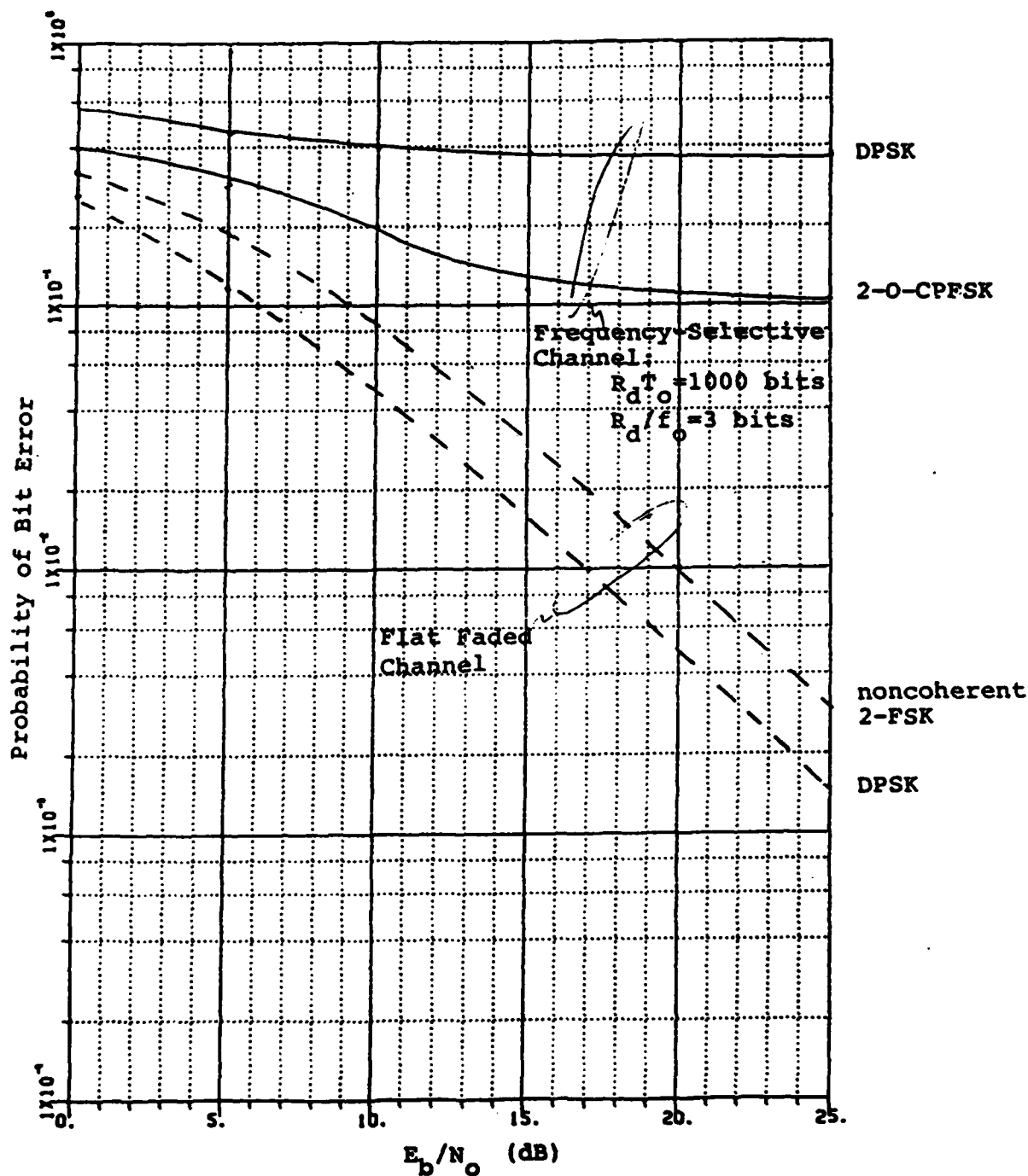
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Figure 4-1   Comparison of DPSK with 2-ary O-CPFSK in
             a selective channel, ($t_o = 1000/R_d$, $f_o = R_d/3$)
             Dashed lines represent Rayleigh flat fading
             channel performance.

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R.T. : 1000.0 BITS
M-ARY : 4. SYMBOLS

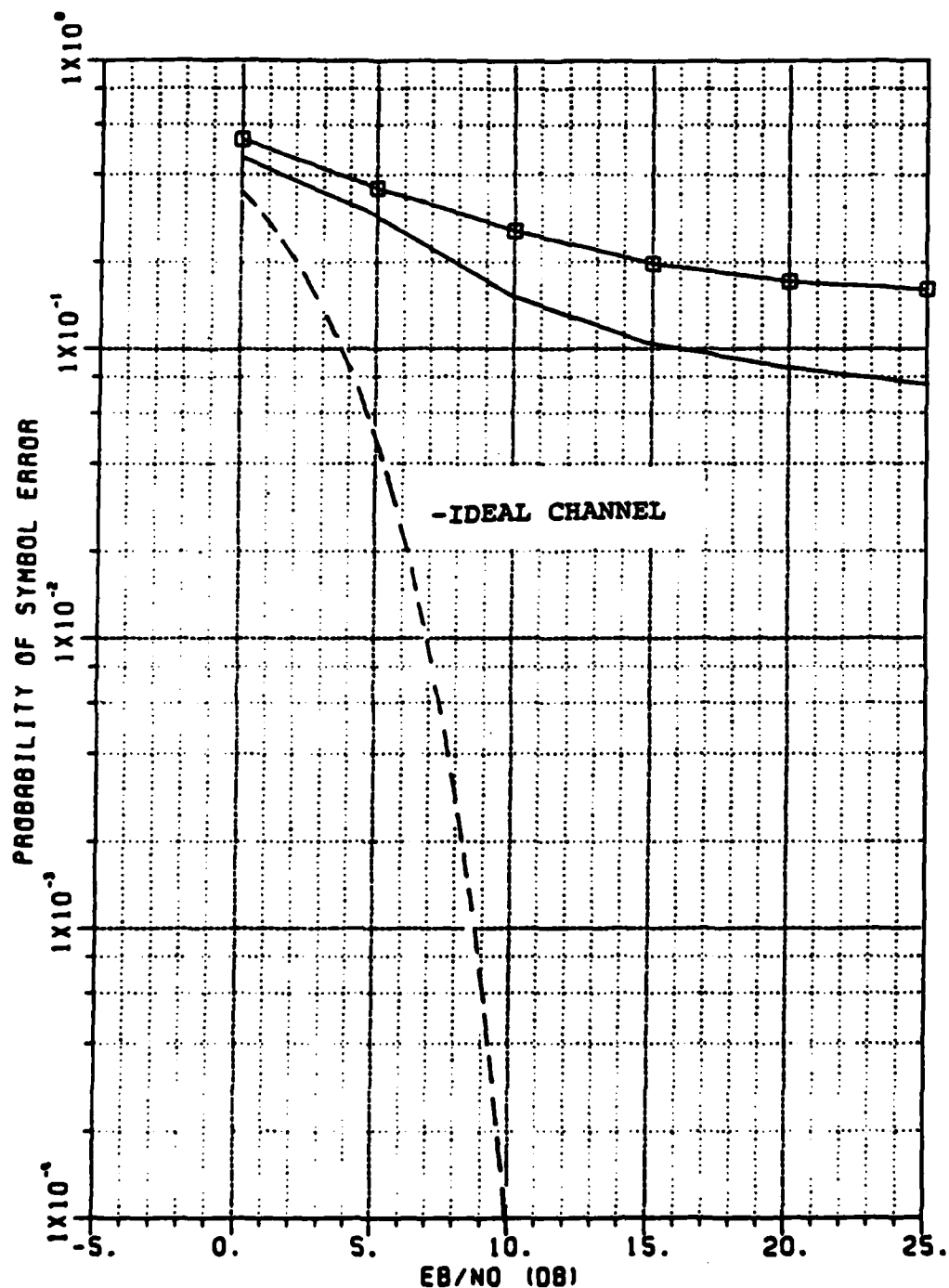─ = NONCOHERENT CPFSK

▢ = NONCOHERENT FSK

Figure 4-2 Comparison of noncoherent 4-ary orthogonal
CPFSK to noncoherent 4-ary orthogonal FSK
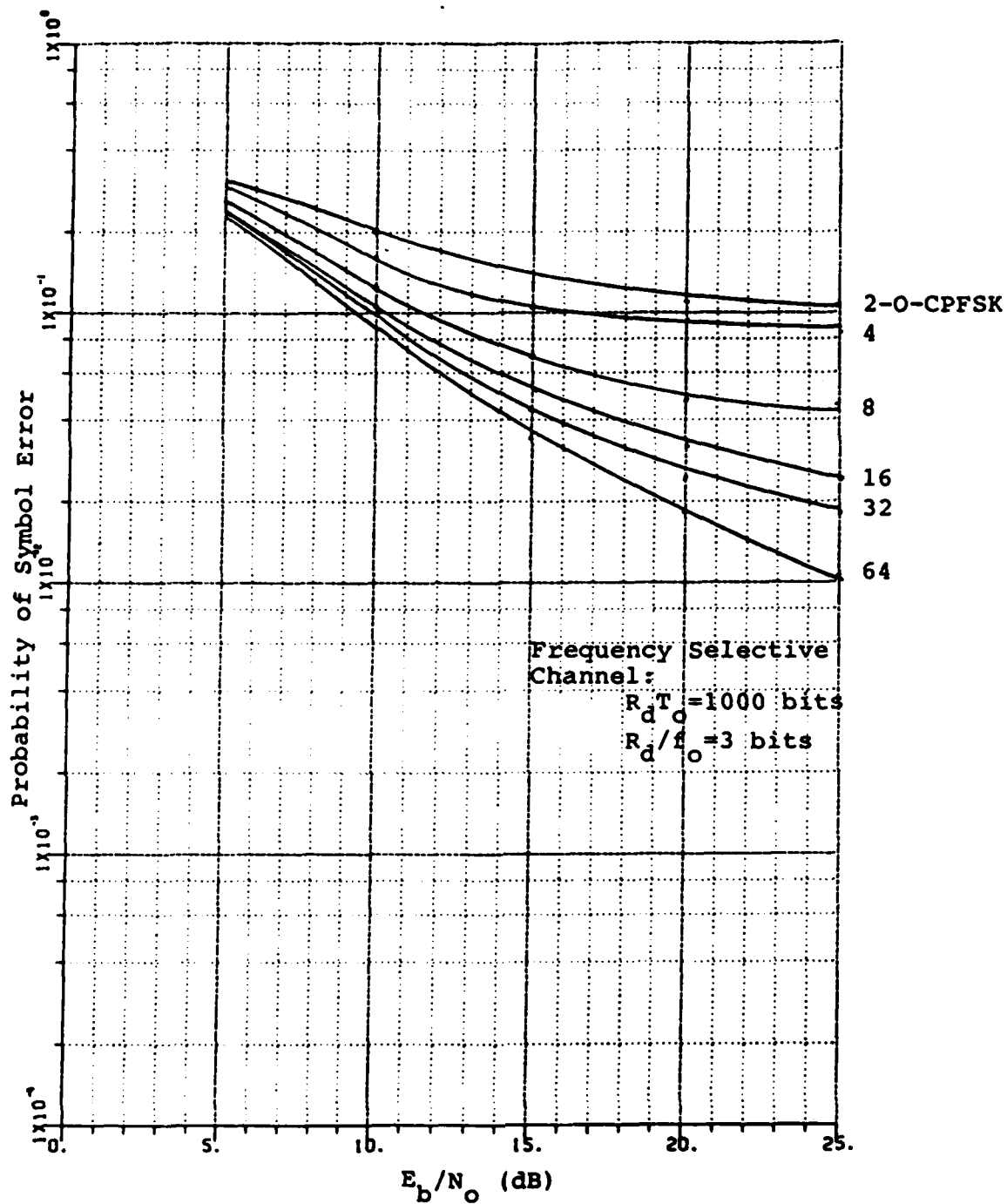in a selective channel. Ideal channel is
dashed line.

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Figure 4-3 Comparison of different signaling set sizes of O-CPFSK in a frequency-selective time-varying channel

In Figures 4-4, 4-5, and 4-6, the simulation results of 64-ary O-CPFSK are compared to DEBPSK using Adaptive Maximum Likelihood Sequece Estimation (AMLSE) with K_{est}=4 and K=4, (see reference [5]) for various R_d/f_o's. Note that in all 3 cases, although the 64-ary performs worse than the equalized modulation, it does well when considering the environment. These results indicate that a possible combination of 64-ary CPFSK with some equalization and/or error correction coding will yield significant results in this environment.
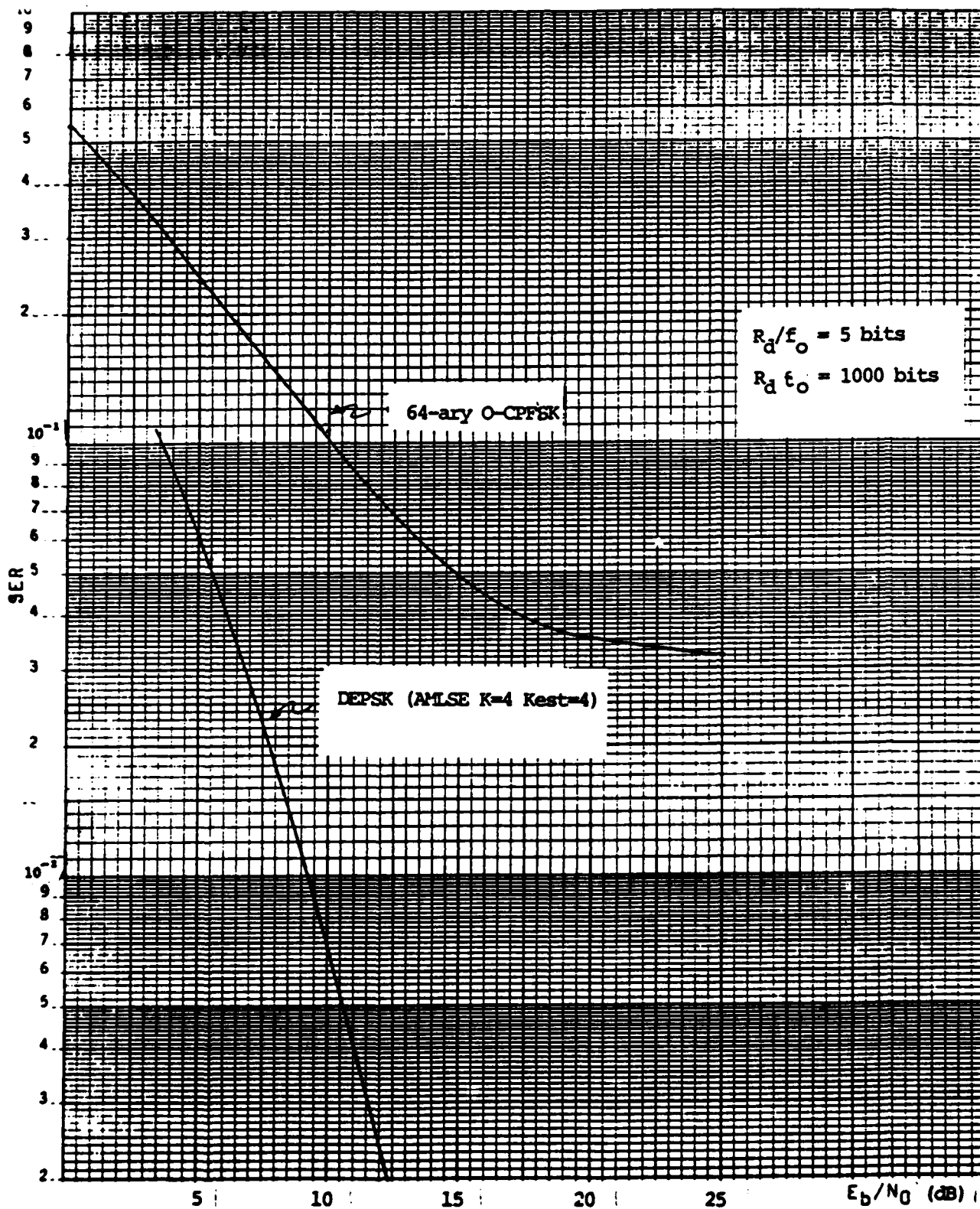
Figure 4-4   Comparison of 64-ary noncoherent orthogonal
CPFSK with DEBPSK using AMLSE (Kest=4, K=4)
in channel with $R_d/f_o = 5$

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Figure 4-5   Comparison of 64-ary noncoherent orthogonal
CPFSK with DEBPSK using AMLSE (Kest=4, K=4)
in channel with $R_d/f_o=12$

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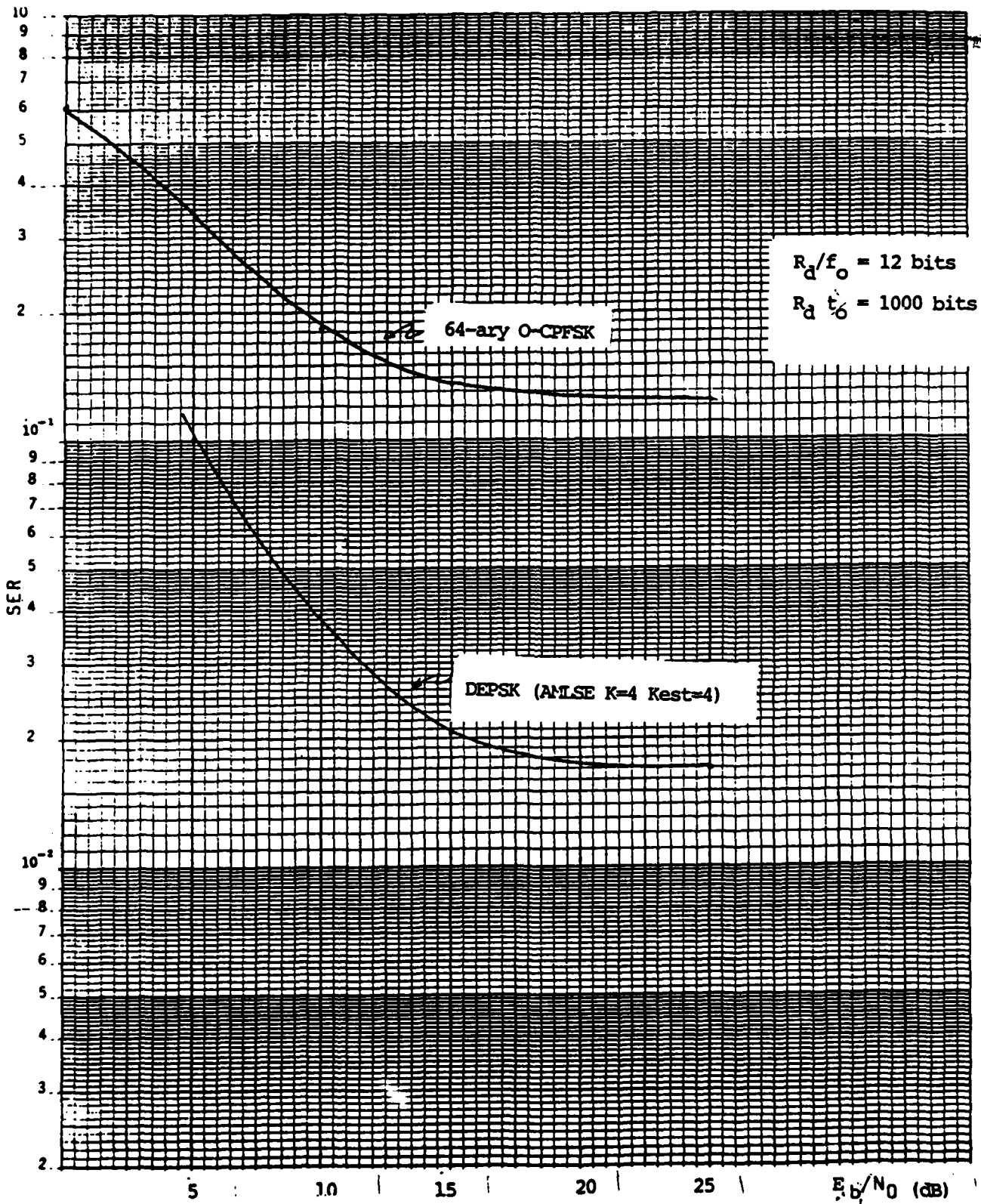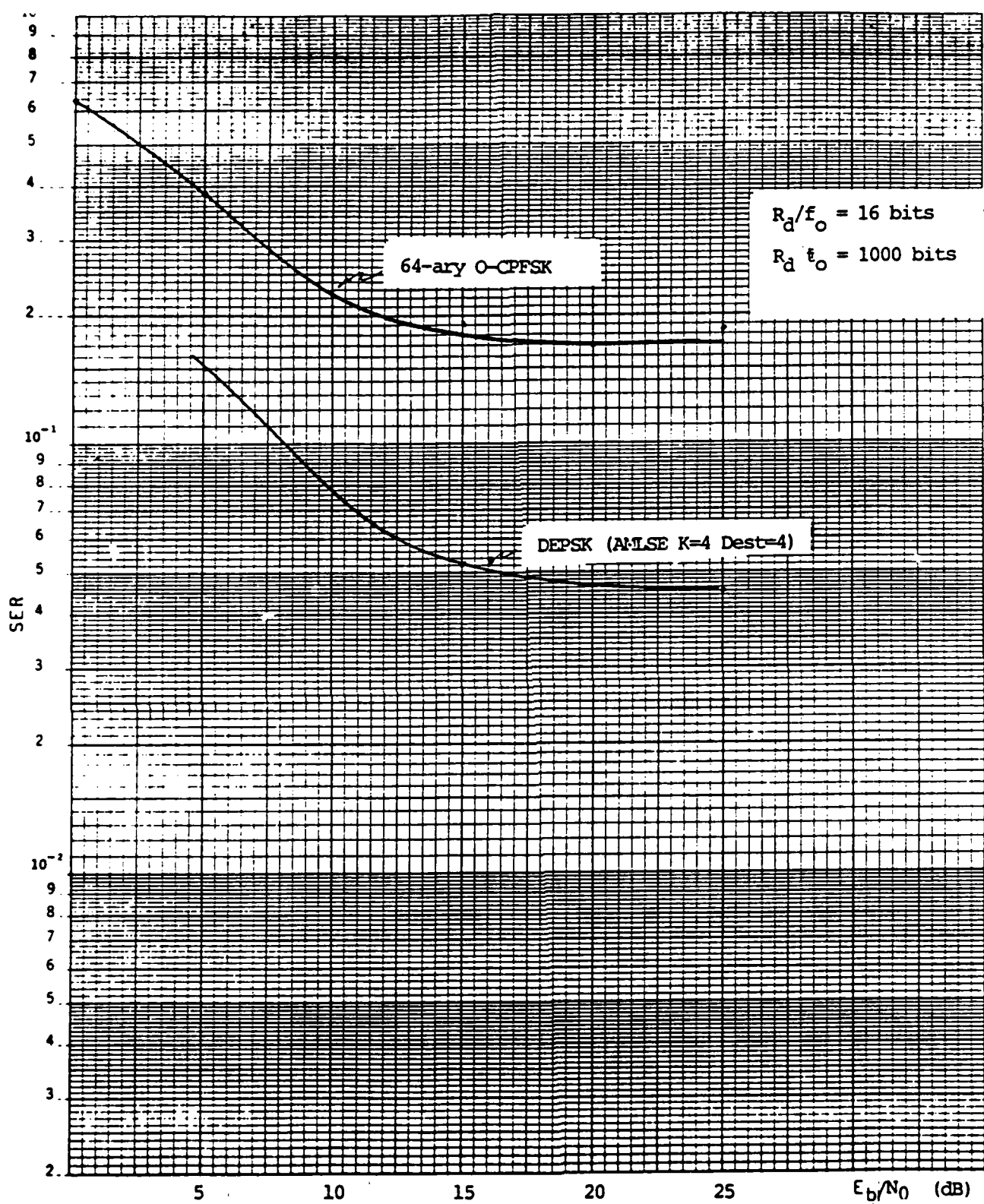
Figure 4-6   Comparison of 64-ary noncoherent orthogonal
              CPFSK with DEBPSK using AMLSE (Kest=4, K=4)
              in channel with R_d/f_o=16

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SECTION 5

CONCLUSIONS

The M-ary O-CPFSK modulation performed well in a selective channel when considering an unequalized/noncoded system. It showed significant improvement over DPSK and FSK without continuous phase. With coding and/or equalization this technique will show performance that meets or exceeds the AMLSE results presented in reference [5]. The only significant problems remaining are implementation practicalities (i.e., nonlinear amplifiers, and intermodulation products, etc.).

SECTION 6

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